ASHESI UNIVERSITY

DESIGN OF A WINDOW CLEANING ROBOT FOR HIGH RISE BUILDINGS

CAPSTONE PROJECT

B.Sc. Mechanical Engineering

ENAM EFOKODZO NANEMEH

2019

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CAPSTONE PROJECT

Capstone Project submitted to the Department of Engineering, Ashesi University in partial fulfillment of the requirements for the award of Bachelor of Science degree in Mechanical Engineering.

ENAM NANEMEH

2019

DECLARATION

I hereby declare that this capstone is the result of my own original work and that no part of it has been presented for another degree in this university or elsewhere.

Candidate's Signature:

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Candidate's Name:

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Date:

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I hereby declare that the preparation and presentation of this capstone were supervised in accordance with the guidelines on supervision of capstone laid down by Ashesi University.

Supervisor's Signature:

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Supervisor's Name:

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Date:

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Abstract

An analysis report compiled by the OSHA lists eighty-eight (88) window cleaning accidents over the past 15 years of which sixty-two (62) resulted in fatalities [1]. Despite these statistics and the potential for injuries and deaths, the industry considers these numbers to be artificially low. Window cleaning is still not effectively regulated, and numerous people undertake this activity in a way that endangers both themselves and the public. This project aims at removing the human component in this life-endangering task by building an autonomous window cleaning robot, The Wall-C, with the capability of scaling walls and skyscrapers with windows. The main task undertaken by this system is to efficiently clean windows on buildings such as glass skyscrapers while systematically moving from glass section to glass section. The focus of this paper though is the manufacturing processes undertaken in the creation of the Wall-C. These included the casting, finishing and assembly operations in bringing the skeletal frame of the window cleaning robot together. The weight of the Wall-C was recorded to be approximately 15 kg, and it had a cleaning rate of 6.156 m^2/hr.

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List of Abbreviations

WBS .... Work Breakdown Structure

RPM .... Revolutions Per Minute

SFM .... Surface Feet per Minute

PLA .... Polylactic Acid

OSHA .... Occupational Safety and Health Administration

CAD .... Computer-aided Design

FEA .... Finite Element Analysis

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Chapter 1: Introduction

An analysis report compiled by the OSHA lists eighty-eight (88) window cleaning accidents over the past 15 years of which sixty-two (62) resulted in fatalities [1]. Despite these statistics, the industry considers these numbers to be artificially low. For window washers, high-rise equipment failure, whether it involves a faulty bosun chair or swinging carriages, is particularly dangerous. Any little mishap while undertaking cleaning tasks on the windows of high-rise buildings usually results in death. Moreover, the wind is a significant problem affecting cleaners as it can easily pick up an individual and blow him/her around dangerously. Due to the minimal advancement in technology in this sector, most companies and landlords of such high-rise buildings are comfortable with the traditional methods of cleaning windows; usually involving an individual at the helm of such endeavors.

1.1 Background

"Architecture makes work by its very being" [2]. Since the beginning of time, megastructures have been built to the wonder of many and with each era and generation, come more significant advancements in the architectural sector. The existence of these structures births the need for proper maintenance, rehabilitation, and physical care. Proper maintenance is the most cost-effective means of extending the life of a building and slows the natural process of deterioration. The use of bricks, concrete and cement blocks in constructing buildings means the occasional painting is needed in its maintenance routine. In more modern designs, however, the use of glass in these structures has become prevalent. Thus, new inventions designed to clean domestic window glasses are gaining popularity since the end of the 19th century. These innovations include the Window-Cleaning Step-Chair, the Extensible Window-Washing Device, the window wipers, and the Hydro Pneumatic Window Cleaning Apparatus. These innovations and inventions highlight the importance of maintaining these architectural designs and the efforts undertaken to ease the cleaning of glass windows. However, for most of these innovations, human involvement is crucial in achieving the desired purpose of the device. Other inventions on the other hand, such as the window wipers tend to destroy the aesthetic value of the building on which it is installed.

1.2 Problem Definition

With the increasing number of glass buildings and skyscrapers in all parts of the world and particularly in Ghana, the need to undertake high maintenance and physical care have likewise increased. In keeping such windows clean, however, many cleaners in Ghana are hired to scale these buildings either using ladders, through the interior of the building or in some rare cases scaffolds. These methods of cleaning windows pose a considerable risk to these individuals as they are easily liable to fall to severe injuries or in the worst cases, death. Moreover, such individuals are unable to clean the windows to the best of their abilities due to the inconvenience posed and reasonable fear. Though this is the most commonly used method for cleaning windows, there are other available alternatives such as the devices or technology employed by some major companies. These include Booms, Carriages, Portable Davits, and Bosun Chairs. Such devices, however, are not viewed as cost-effective by some firms and still involve the presence of a human being to clean the windows [3]. Though the risk is minimized, it is still very much existent.

1.3 Objectives of The Project

This project aimed to design and build an autonomous window cleaning robot, the Wall-C, with the capability of scaling walls or skyscrapers with windows. Its task is to efficiently clean windows on buildings such as glass skyscrapers while systematically moving from glass section to glass section.

1.4 Justification/Motivation for Project Work

The risks and dangers faced by cleaners when cleaning windows on glass buildings are immense as they are easily liable to fall to severe injuries or their deaths. This project thus aims at designing and developing a window cleaning robot that can scale such skyscrapers. The need for human beings to engage in such tasks would be eradicated, hence the risks faced by such individuals eliminated.

1.5 Research Methodology and Resources Used

The research methodology employed in this project was primarily experimental. The Wall-C cleaning robot was designed, built and tested against variables such as the speed, weight and surface area covered by the cleaning apparatus. It was then compared to similar cleaning devices obtained from literature reviews. The SOLIDWORKS 3D CAD software was used to design the Wall-C and get the robot dimensions and estimated values for the cost and weight of the robot. A Pugh matrix was also employed to determine the most appropriate material to use in the project design.

Chapter 2: Literature Review

Since the end of the 19^{th} century, new inventions designed to clean domestic window glasses gained popularity. These innovative inventions included Anna Dormitzer's technically successful Window-Cleaning Step-Chair (1878). This design combined a short stepladder with a seat at its top that could be hung over a windowsill. The stepladder allowed the cleaner to sit and clean the windows from the outside [2]. Another invention that succeeded this design was the Extensible Window-Washing Device which used a scrubber, a metal 'lazy tongs' and a hand crank to reach areas of window exteriors that were otherwise unreachable. Another device adopted was the Hydro Pneumatic Window-Cleaning Apparatus. In 2002 though, Vanessa van Dam, a Dutch artist created a window washing installation designed for a site near Schiphol Airport, Amsterdam. Eighty-five (85) industrial-sized window wipers were proposed to be installed on the building's windows. These wipers were to be choreographed to a programmed script that would be activated by sensors responding to local weather conditions – especially rain [2]. More modern and common designs preferred by most companies include the Booms, Carriages and Bosun Chairs. These window cleaning devices, however, require the involvement of an individual whereas other devices such as Vanessa van Dam's window wipers tend to diminish the aesthetic value of the architectural structure on which it is installed.

More recently though, they have been advancements in automating a window cleaning robot so human involvement would reduce. One such invention is the window cleaning robot designed by Houxiang, Jianwei, and Guanghua (2006). The most prominent feature in this design was the use of pneumatic technology. This technology has been adopted by most developers because it is less costly, has a high power-to-weight ratio and is much cleaner than the alternatives. However, pneumatic systems have the characteristic of nonlinearity which makes it challenging to implement precise position control [4]. Thus, the authors of the journal of the window cleaning robot aimed at developing a pneumatic robotic system for cleaning the glass walls of high-rise buildings.

Moreover, the lower stiffness and non-linear movement characteristic of pneumatic systems are solved by implementing an accurate control of the pneumatic X-cylinder-position servo system through a variable bang-bang controller. This was significant to the proposed project since it was previously decided that pneumatic actuators would be used in the movement mechanism of the robot. Though the pneumatic actuators were later replaced with electric linear actuators, the processes involved in implementing the movement mechanism of the robot are similar.

The robotic system designed which was named Sky Cleaner 3, included a supporting vehicle, a following unit, and a cleaning robot. The following unit was attached at the top of the working target; a building 40 meters from the ground and a total surface area of roughly 5000m^2. This following unit had cables running down to the cleaning system and tracked its movement as it traveled across the building. The supporting vehicle was fixed on the ground and consisted of long hoses for the flow of water, long tubes for pressurized air and cables for the control signals which control the movement of the cleaning system. It was noticed, however, that the wires and hoses running from the supporting vehicle to the cleaning robot would carry some weight, due to the water and pressurized air flowing through them, which would contribute to the total weight of the cleaning system when in mid-air. Concerning the cleaning robot though, it featured fourteen (14) suction pads which could carry a load of approximately 60 kg, four brush cylinders and a few sensors which could detect window obstacles. Thus, as water flows down the building due to the force of gravity, the brush cylinders actuate the vertical movement of the brushes to allow for a more thorough cleaning process. The sensors which detect the window obstacles would inform the progress of the cleaning robot so that there is no impediment on the path the robot takes.

The water which flows down the building is then collected at the bottom in a basin attached to the supporting vehicle on the ground which is then filtered and reused for cleaning.

Moreover, a programmable logic controller is used for the robot control system due to its high stability and modularity [4]. The PLC keeps track of the pulse signals produced by the encoder and drives the relays, vacuum ejectors and solenoid relays. Vacuum sensors are also used in the system to monitor the vacuum condition for each suction cup. The sensors would then inform the system regarding which suction cup would need air sucked out of it and which would not. When the air has been completely removed from the suction cup, it sticks firmly to the building making the cleaning system stable mid-air.

Furthermore, the vacuum sensors enable the determination on whether the suction on the glass is stable. In effect, as the robot system moves across the building, the suction cups keep it firmly fixed to the structure. The cleaning trajectory used by the robot is coded specifically to the design and shape of the surface area. With the working target used by the robot, the authors designed the robot to start its movement from the upper left point of the building. The robot system then travels and cleans in the vertical direction downwards. At the end of the vertical path, it then moves to the next column and repeats the same process. The coverage percentage on the working area used by the robot system was over 93%, and the cleaning efficiency was 125 m^2/hour [4].

The cleaning robot was designed to be fully pneumatic because, with the use of pneumatic actuators, the climbing robot can be made to be lightweight and handy. However, there is a significant challenge in controlling pneumatic valves in that there are several complexities involved when the control system deals with hysteresis. Thus, the authors employed a closed loop control system to control the solenoid valves by using delay times to open and close the valves. The results obtained during the testing phase showed that the use of the variable bang-bang controller significantly improved the control quality of the cleaning robot. Indeed, their paper highlighted the effectiveness of various mechanisms essential in designing an efficient window cleaning robot. A few of such devices to be employed in the proposed project design included the use of suction cups, solenoid valves, and linear electric actuators. Thus, the paper clearly outlined the benefits of using such devices and the drawbacks some of them possess. However, the cleaning robot mid-air was bulky as it weighed 60 kg and the numerous devices which culminated in the final product were multiple and quite expensive. Thus, the proposed project design aims at developing a simpler cost-effective model which would weigh much lesser than the Sky Cleaner 3.

A simpler implementation of a climbing robot was undertaken by Albagul, Asseni, and Khalifa (2011). Their article focused on the mechanical design and implementation of a wall climbing robot. It describes the design and manufacture of a quadruped climbing robot. The robot designed by these authors also used suction cups as a means of sticking to the wall, and in the movement of the body, two servo motors were used. Each servo motor controlled the legs located at either side of the robot. By using a slider and a crank, the leg movements mimicked stepping motions and enabled the progress of the robot along the incline [5]. The suction forces required for each of the four suction cups attached to the robot were provided by two vacuum pumps that turn on intermittently. This process was explicitly designed in such a manner so that all four suction cups were not sticking to the wall at the same time. The main body of the robot created by these authors was meant to carry all the components used in its functionality except for the compressor. The robot was thus mobile and more portable.

Despite the simplicity of the design, some challenges came with this design. These included the fact that the material used in the design of the suction cups was aluminum and so welding the fittings together was challenging. Moreover, an Energizer 9V battery was used to power the system. This battery, however, ran out very quickly and was costly. This battery was also housed on the body of the robot and contributed to the weight of the system. The load exerted more stress on the servos and required the use of high torque to move the climbing robot. Finally, the robot was designed to move only linearly inhibiting the maneuverability of the system as a cleaning system was not included in the design. In light of this, with the proposed project design, a 12V battery will be used which would be housed on a separate supporting unit fixed on the ground. Thus, the cleaning robot would meet its requirement of being light in weight and the power provided to the system would not deplete substantially. Moreover, to enhance the mobility and maneuverability of the robot, two linear electric actuators would be used so that the robot could move linearly in the X and Y directions. By adding another directional motion to the robot, the cleaning done by the system would be more efficient.

Another paper used in informing the design and functionality of the proposed project design was a report written by Ori Barbut (2008) for the ASME Design competition in 2008. The robot was designed to be lightweight and to clean a double-hung sash window as fast as possible [6]. The robot design employed the use of a set of parallelogram 4-bar linkages and plastic in manufacturing the frame. The robot also used wheels that had soft urethane tires, which provided the frictional force which kept the robot in place. A cleaning pad was also used to erase any stain or dirt on the windows. To make the replacements of the cleaning pad easier and faster, the pad was mounted with a hook on a sheet placed at the front of the robot. The robot also used a winch mechanism in lifting itself between window panes and any other obstacle in its path. The robot designed was simple, and it was also small and light in weight.

However, there were a few challenges and gaps observed in the design of the robot. The cleaning system did not use water or any cleaning solution in its cleaning process. This would be quite problematic as some stains or dirt would require the use of a solution before they can come off. Besides, the use of just the cleaning pad could cause the smearing of dirt across window surfaces. Furthermore, the use of wheels alone in keeping the robot fixed to the target area would not be considered safe. Due to the weight of the proposed project design, the use of adhesive wheels alone would not be enough to keep the robot firmly attached to the window panes. This was particularly insightful with regards to the proposed project in that it further reinforced the idea of using suction cups as a means of keeping the robot firmly attached to the target area.

Indeed, these papers and journals adequately informed the most appropriate tools and devices to be used when implementing the Wall-C project design. With the existence of varying methods and design processes, it is imperative that the most efficient model is used, as the cleaning robot is required to clean high rise buildings and thus would travel long distances.

Chapter 3: Design

3.1 Review of Existing Designs

Despite the advancement of technology, there has hardly been any breakthrough in the window cleaning sector. Be it the cost and practicality of existing technology or the comfort with regards to the traditional methods of cleaning windows, many companies and owners of high rise buildings face difficulties in adapting to the implementation of technology in this area of basic maintenance. One of such traditional methods used in cleaning windows includes the Bosun Chair. The Bosun chair is a modern invention designed for a single cleaner. This invention allows the cleaner to have access to tight areas of a window glass surface and is ideal for prolonged and dedicated cleaning [7]. Another design commonly used is the Boom. The Boom is a structure fixed at the roof of the building which can hold multiple cleaners at the same time. However, it is a permanent structure and cannot be moved and thus is used as and when it is needed [7]. An alternative invention that is increasingly becoming popular is the Carriage. The Carriage is an advanced version of the Boom in that the structure fixed at the roof of the building can be moved laterally across the façade. This design could also accommodate several cleaners at a time.

However, the common danger present in these methods employed by the various companies is the use of human labor in undertaking such cleaning tasks. At high altitudes, the existence of high-velocity winds and bugs could prove to be a nuisance to these workers. The use of humans in performing this cleaning task could also be endangering to one's life as an unfortunate incident could cause a worker to fall from such heights. It was reported in the 2008 New York Times magazine that two window washers had been stuck on a scaffold outside a Times Square high-rise. Within hours of their rescue, a window cleaner who had been at the job for twenty (20) years fell to his death from a 17-story building [8]. Indeed, experience at the job does not guarantee that one's life is not at risk when undertaking such a profession. Moreover, within the past 25 years, it has been reported that ‘non-union workers have had about 200 accidents, including more than 70 fatalities’ [8]. Given this, it is imperative that an alternative is designed for cleaning the windows of high-rise buildings to minimize or better yet eradicate the need for human involvement. Thus, this paper describes the development of an efficient window cleaning robot capable of scaling high rise buildings. The focus, however, was on the manufacturing processes undertaken in creating the Wall-C. The methods included the casting, finishing and assembly operations in bringing the skeletal frame of the robot together. Moreover, the design focused on reducing the weight and cost of the Wall-C so that it is much lighter and cheaper than other similar inventions.

3.2 Design Decisions

To develop an efficient functioning model, different specifications were considered regarding the design, functionality, appearance, and practicality of the project design. Considering this, both the system and user requirements were laid down to regulate the thought process and the design decision making processes. Moreover, a work breakdown structure was used to proficiently divide tasks into their appropriate regions and assign a time range for each specific task.

3.2.1 System Requirements

The system requirements regarding the Wall-C project design are as follows:

- The project model should be electrically powered (battery-powered) to promote the use of clean energy.
- The model should be durable.
- It should be relatively lightweight so that it is not cumbersome.

- The model should be scalable and hence should possess the trait of being easily modified.
- The product should be highly responsive to the signals sent with regards to its movement and functionality.
- The model should be secure and have safety measures to avoid danger to the user or third parties.

3.2.2 User Requirements

User requirements were also formulated as this informs the relevance of the project design. The user requirements per the model are as follows:

- The project model should be able to scale the walls of high rise buildings as efficiently and quickly as possible.
- It should be able to clean the glass windows of buildings efficiently; it should be able to clean a large surface area of the window pane at a fast rate.
- It should be able to last an hour with a single charge if the system is rechargeable. If a battery is used, the battery should be changed as conveniently and efficiently as possible.
- The system should be easy to operate.
- The cost of the entire system should be relatively low and affordable.

3.2.3 The Work Breakdown Structure

To graphically portray the structured manner in which the project was to be undertaken, a Work Breakdown Structure (WBS) was designed. The WBS was created so that each main activity was broken down into much smaller operations and thus the risk of glossing over a specific task essential to the success of the project was minimized. As observed in Figure 1, the WBS highlighted the need for coming up with a 3D conceptual design. The 3D conceptual design, however, was dependent on the fact that the project design was divided into two phases: the climbing phase and the cleaning phase. These two phases though were considered under yet another separate entity of the project design: the hardware component. The other entity that was critical to the success of the project was the software component, as this was the primary driver with regards to the movement and functionality of the design. The WBS as observed in Figure 3.1 gave a vivid picture of the tasks to be performed and informed the project schedule and timeline.

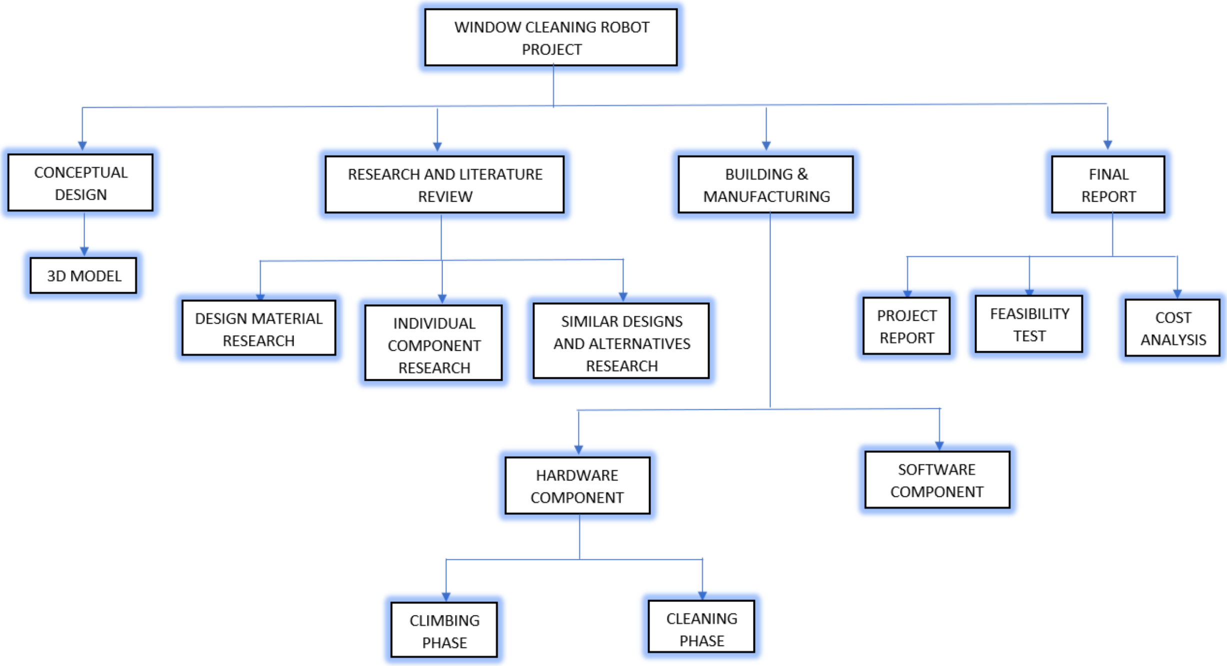

Figure 3. 1: The Work Breakdown Structure (WBS)

3.2.4 The Pugh Matrix

Table 3. 1: Pugh Matrix used to determine the appropriate material

Description Criteria	**Annealed Steel**	**Aluminium Alloy (1060)**	**Plastic (PLA)**
Total Weight	-3	0	+2
Yield Strength	-1	0	-4
Tensile Strength	+2	+1	0
Cost	-2	0	+1
Manufacturability	+1	+2	-1
Availability	+2	+1	0
Net Score	**-1**	**+4**	**-2**

A Pugh matrix, as observed in Table 3.1, was used to compare the various materials that were proposed to be used for the Wall-C robot. The materials under consideration were Annealed Steel, Aluminium Alloy (1060) and Plastic (PLA). The characteristics used to determine the most appropriate material were the total weight, Yield strength, Tensile Strength, Cost manufacturability and availability. Plastic (PLA) was seen to be a suitable option due to its lightweight and inexpensiveness. Annealed steel, on the other hand, had the highest tensile strength and was more available. However, Aluminium alloy (1060) had the highest yield strength, was cheaper than steel and was the easiest to work with in terms of its manufacturability. Thus, Aluminium alloy was selected to be the most appropriate material to use for the fixtures in the skeletal frame of the window cleaning robot.

3.3 Design Components

Based on the literature reviews, system, and user requirements, it was imperative that the project design was lightweight, practical and efficient. Thus, the items used in formulating the project design are as follows:

- **Eight (8) Thin Layered Female Fiber Suction cups**: A pair of these suction cups are attached to each leg of the cleaning robot. These serve to keep the robot firmly fixed to the target area using air as the driving agent. They also provide the grip needed to climb the glass panel.
- **Six (6) Tee connectors**: These are used to properly align and direct the tube carrying the pressure from the vacuum pump to the various suction cups.
- **150 Psi Vacuum Pump (220 VAC)**: This device provides a region of negative pressure at an inlet through the creation of a vacuum. It is used to supply and isolate air to/from the suction cups to regulate their attachment to the surface area.
- **Four (4) 12V 20AH Batteries**: These are used to power the electrical devices on the robot.
- **Thin and hollow aluminum metal rods**: These rods are used to design the movement mechanism of the robot. They are made hollow to contribute to the lightweight characteristic of the entire system.
- **Two (2) 12 VDC Electric Powered Linear Actuators**: These are the main drivers for the moving mechanism. They extend and contract iteratively to move the robot in the X or Y direction.
- **Four 300 mm plastic wipers:** These are attached to the legs of the robot to clean the window surface as the robot travels across the surface of the glass panels.
- **A 12 VDC water-pump**: This device is used to feed the cleaning solution to the sprinkler to be sprayed on the window surfaces.
- **A reservoir**: This serves as the storage tank for the cleaning solution that will be used to clean the window surfaces.
- **Water Sprinkler**: This device sprinkles the cleaning solution on the window surfaces.

- **Aluminum sheets**: The aluminium sheets would be used to build the following unit which will house the battery, compressor and other bulky apparatus.
- **Four wheels**: These wheels are attached to the following unit which eases the mobility of the following unit.
- **Wires**: These are used in the electrical set up of the system.
- **Tubes**: These are used to aid in the transport of the cleaning solution and air to the sprinklers and suction cups respectively.
- **Wooden beams**: These wooden beams would be used to build the skeleton of the following unit which would house the battery, compressor and other bulky devices.
- **Aluminum Casted Fixtures**: These fixtures are meant to hold the guiding rods in place and provide support for the suction cups and the water sprinkler.

3.4 Design Iterations

Before the implementation of the project design, different design iterations were formed using the SOLIDWORKS software. Different iterations were created so that each model could be analysed, tested, simulated and refined to arrive at the most efficient design. Moreover, a 3D CAD model of the Wall-C made the manufacturing of the robot easier. Two main design iterations were modelled.

3.4.1 First Iteration

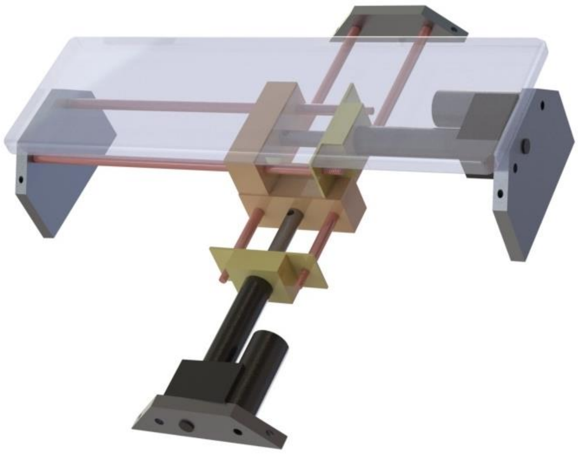

Figure 3. 2: First Iteration SOLIDWORKS model of the window cleaning robot

As observed in Figure 3.2, the first iteration of the design included two pneumatic double acting actuators which are attached adjacent, using aluminum rods. Both actuators are programmed and positioned to move in both the X and Y directions simultaneously. However, the movement of one actuator does not impede the progress of the other actuator. Two suction cups are attached to each leg of the robot so that the design is fixed on the target area at any specific time. A brush/wiper is also connected to each leg so that as the robot moves in any direction on the target area, the brushes clean the surface area simultaneously. A water sprinkler is attached to the board or cover on the robot and sprinkles water intermittently from the reservoir with the aid of a water pump. In effect, with the movement of the robot across the target area, the surfaces of the windows are cleaned simultaneously. The fixtures that support the suction cups and the rods are also built out of wood. The following unit is created using the wooden beams which house the compressor, water reservoir, water pump, and the battery. As the robot moves across the window surfaces, the following unit follows closely on the ground level. The use of a compressor is proposed to suck out or provide the air to the area between the suction cup and the mounting area. When air is isolated from the suction cup, it sticks firmly to the mounting surface. On the other hand, when the air is pumped into the area between the suction cup and the mounting area, the suction cup loses its adhesive nature.

3.4.2 Second Iteration

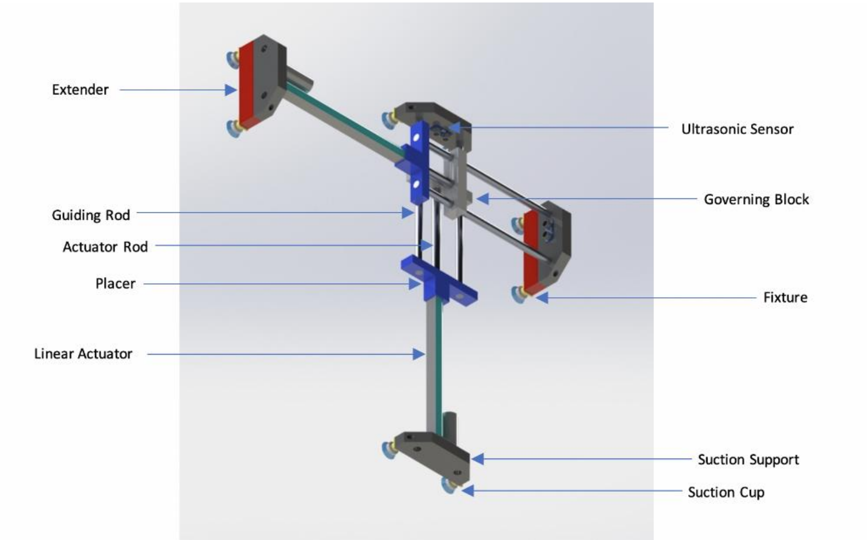

Figure 3. 3: Second iteration of the robot frame

The second and final iteration of the design as observed in Figure 3.3 included modifications to the materials used for the fixtures and the components that would make up the window cleaning robot. The two (2) pneumatic double acting actuators were replaced with two electric powered linear actuators because the pneumatic actuators were unavailable. The use of Four (4) batteries will be retained as they would be enough to power both electric actuators and other electronic components. The materials to be used in designing the fixtures were also changed from wood to aluminum. Wood has the characteristic of absorbing water and the backsplash when water is sprinkled on the window surfaces could end up on the wooden fixtures. Thus, to increase the longevity of the fixtures, it was proposed that they are made from aluminum. A vacuum pump was also intended to be used instead of the compressor as modifications were required to be undertaken on the compressor so that it could act as a vacuum pump. Moreover, because of the change from pneumatic to electric actuators, various dimensions had to be accounted for in the entire structural design.

3.5 Design Analysis

Table 3. 2: Estimated Weight of the parts in the Skeletal Frame of the Robot

Quantity	Part Reference	Mass (kg)	Mass * Quantity (kg)
4	Guiding Rod	0.21755	0.8702
2	Placer	0.37775	0.7555
2	Governing Block	0.36833	0.73666
4	Suction Support	0.71341	2.85364
2	Extension	0.48524	0.97048
	TOTAL:	**2.16228**	**6.18648**

Table 3.2 depicts the estimated weight of the second and final iteration of the project design. The weight of the design was estimated to be 6.186 kg. The weight though only accounted for the masses of the Guiding rod, Placer, Governing Block, suction support and Extension. The masses for the linear electric actuators, tubes, wipers, water, and air flow were not accounted for, and so it was imperative that the weight of the fabricated Wall-C cleaning robot would be much higher. Thus, for the significant part of the analysis and calculations, a mass value of 15 kg was assumed.

Based on the weight of the system, the minimum pressure required to keep the robot firmly fixed to the window pane had to be calculated. The calculations were as follows:

$$\boldsymbol{Pressure = \frac{Force}{Area}}$$

$$\boldsymbol{Area = \pi r^2}$$

$$\boldsymbol{Actuator\ Speed\ (V) = \frac{Stroke\ Length}{Time\ Taken}}$$

$$\boldsymbol{System\ Flow\ Rate\ (Q) = VA}$$

$\boldsymbol{\rho_{air}}$**=1.225 kg/m³**

$\boldsymbol{\rho_{water}}$**=1000 kg/m³**

Suction Cup diameter = 3cm;

$$Suction\ Cup\ Area = \pi 1.5^2$$

$$\boldsymbol{Suction\ Cup\ Area = 7.0686cm^2}$$

Since there are eight (8) suction cups:

$$Total\ Suction\ Cup\ Area = 8 \times 7.068$$

$$\boldsymbol{Total\ Suction\ Cup\ Area = 56.544cm^2}$$

Actuator Speed = 5.7mm/s

$$System\ Flow\ Rate\ (Q) = (0.0007068) \times (0.0057)$$

$$System\ Flow\ Rate\ (Q) = 4.02876 \times 10^{-6} m^3/s$$

$$Mass\ Flow\ Rate\ (Air) = 1.225(4.02876 \times 10^{-6} m^3/s)$$

$$Mass\ Flow\ Rate\ (Air) = 4.935 \times 10^{-6} kg/s$$

For a given time of 60 seconds:

Mass (air) = $\mathbf{2.961 \times 10^{-4}}$ **kg**

For Water:

$$System\ Flow\ Rate\ (Q) = 240\ L/h$$

$$System\ Flow\ Rate\ (Q) = 6.67 \times 10^{-5} m^3/s$$

$$Mass\ Flow\ Rate\ (Water) = 1000(6.67 \times 10^{-5} m^3/s)$$

$$Mass\ Flow\ Rate\ (Water) = 0.0667 kg/s$$

For a given time of 60 seconds:

Mass (Water) = 4.002 kg

Total Mass on Climbing Unit = 4.002 + 2.961×10^{-4} + 6.18648

= 10.189 kg

Assuming a total mass of **15kg** (Due to other miscellaneous masses):

$$F = mg$$

$$F = 10.189 \times 9.81$$

$$F = 99.952\ N$$

$$Pressure = \frac{Force}{Area}$$

$$Pressure = \frac{81.686}{5.6544 \times 10^{-3}}$$

$$\boldsymbol{Pressure = 17676.835\ Pa}$$

Hence the pressure required to keep the robot firmly attached to the window pane is **17676.835 Pa.**

Chapter 4: Implementation (Manufacturing Processes)

Following the finalization of the design of the window cleaning robot, the manufacturing phase of the project design was ushered in. The manufacturing of the window cleaning robot was divided into three different stages: the building of the following unit, the creating and finishing of the aluminum fixtures and the assembly of the robot components.

4.1 The Following unit

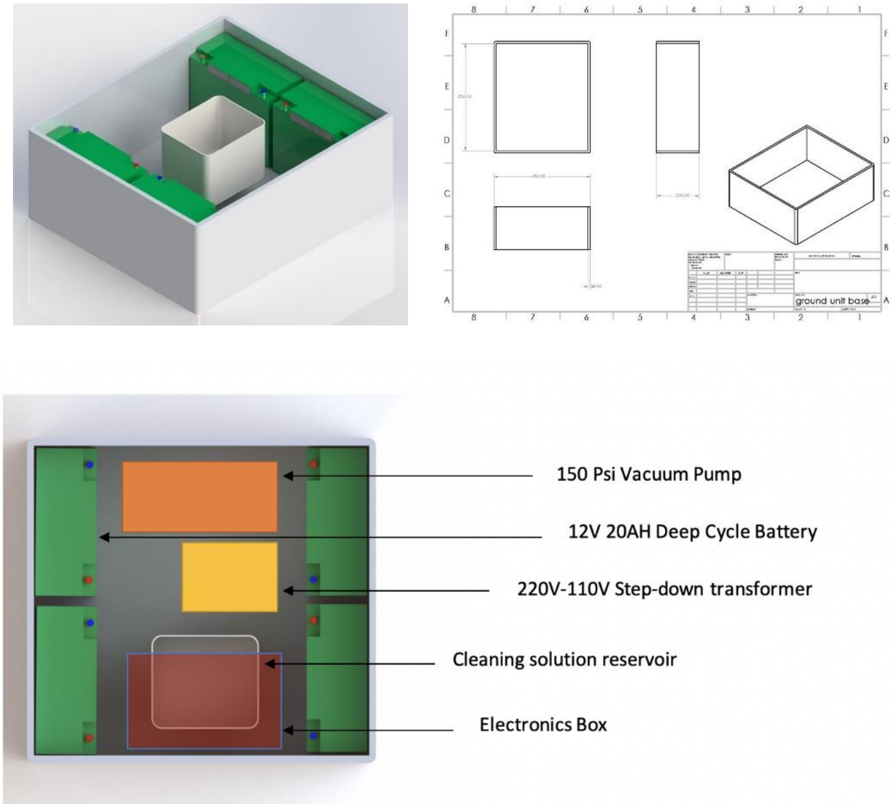

Figure 4. 1: Design and Engineering Drawing of the following unit

The following unit was designed to house the 150 Psi vacuum pump, the four 12V 20AH Deep Cycle Battery, the 220V-110V Step-down transformer and the cleaning solution reservoir. Thus, it was imperative that the structure for the following unit was robust enough to hold all these items. Considering this, long wooden pieces were cut out using a woodcutter to form the skeletal structure of the unit. These wooden beams were then smoothened using a surface planer. They were then further cut according to the dimensions as observed in Figure 4.1. Hence, the wood pieces were nailed together to make up the frame of the following unit. Plywood was then attached to the base of the structure which was further reinforced with three long beams. To complete the structure and improve its aesthetic characteristics, aluminum sheets were used to cover the sides of the structure leaving only the top surface open. Finally, four wheels were attached to the base of the following unit to ensure that it is mobile. The final manufactured design is as seen in Figure 4.2.

Figure 4. 2: Manufactured Design of the Following Unit

4.2 Aluminum Fixtures

It was decided that the fixtures which would hold the guiding rods in place would be made from aluminum to increase its longevity. Additionally, amongst the alternatives to wood, though aluminium was more expensive to fabricate, it was more accessible, more cost-effective and easier to work with. Since the fixtures were customized based on the project design, it was proposed that the fixtures should be cast. Moreover, due to the complications in making an internal cavity, the placer holding the actuator in place had to be divided into two so that a more accurate dimension could be cut out in the fixture as opposed to the alternative, casting. However, before the aluminum fixtures were cast, molds had to be created, whose geometry determined the shape of the cast part. The molds were made from wood as observed in Figure 4.3.

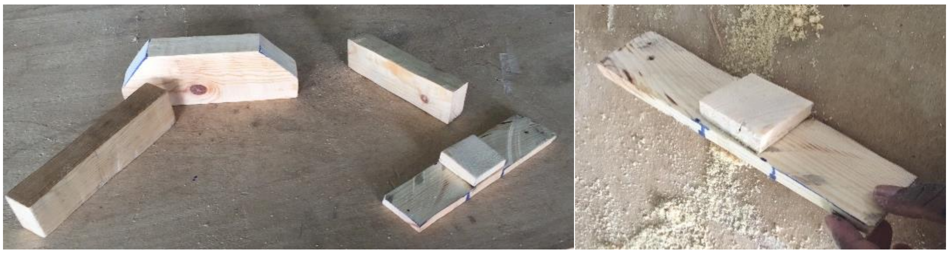

Figure 4. 3: Wooden moulds created to be sent for casting

For each fixture, one mold was made as multiple pieces could be cast from only a mold. The actual size and shape of each mold were slightly enlarged (by approximately 5mm on each dimensional parameter) to allow for shrinkage of the aluminum during solidification, machining allowances and cooling as well as any defects that were bound to occur. Thus, with the aid of a woodcutter and a surface planer, wooden molds were created and sent for casting. The casting method employed by the foundryman was that of a closed mould. In a closed mould, a passageway, called the gating system which includes the down sprue and runner is created to allow the molten metal to flow from the outside into the cavity. The closed mould process was more appropriate than the alternative, the open mould (where molten aluminium is poured until it fills the open cavity) because the geometries of the moulds were quite complex. The overview of the casting technology used to create the aluminium fixtures is as observed in Figure 4.4. The cavity in the sand mould was formed by packing sand around a pattern and then separating the mould into two halves and removing the pattern. The internal surfaces of the fixtures were to be machined, and thus a core was not included in the mould. During the casting process, time is required to complete the phase change from molten liquid to solid and considerable heat is given up. During the solidification process, the molten aluminium assumed the solid shape of the mould cavity. After the cast pieces have cooled sufficiently, they were removed from the mould to be further processed.

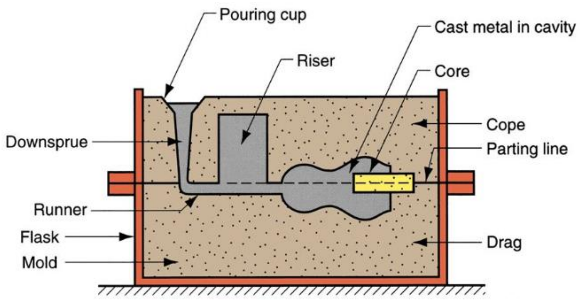

Figure 4. 4: Closed Sand Casting process [9]

Before the casts were sent, the sprues, runners, risers and parting-line flash were removed – a process called trimming. With the arrival of the aluminium casts, the disadvantages of casting could be seen. It was evident that poor dimensional accuracies and surface finishing were present as a result of the casting process used: sand casting. Moreover, defects were visible on all the cast pieces as observed in Figure 4.5. The defects most apparent on the cast pieces were wash and cuts, drop, shifts or mismatches, pinholes, and hot tears. The defects arose not only due to the sand casting process but also because of the removal of external pieces such as the gating system and the riser.

Figure 4. 5: Cast aluminium fixtures

Due to the state of the cast pieces, further finishing processes had to be undertaken which included trimming any excess piece from the actual cast part, cleaning the surface, inspecting the cast parts and machining to achieve closer tolerance and to remove portions of the cast surface. To carry out these processes, a milling and drilling machine was employed as observed in Figure 4.6.

To obtain the right speed to run the Milling machine, the Milling machine Speed (RPM) Formula was used. The RPM formula is as follows:

$$\textbf{Speed (RPM)} = \frac{SFM * 4}{D}$$

Where;

SFM = Surface Feet per minute (This is dependent on the material being milled)

D = The diameter of the milling bit (inches)

The SFM for aluminium is 250 and thus to obtain the speed that the milling machine would be run, the diameter of the milling bit would have to be obtained. This was done to operate the device efficiently and safely.

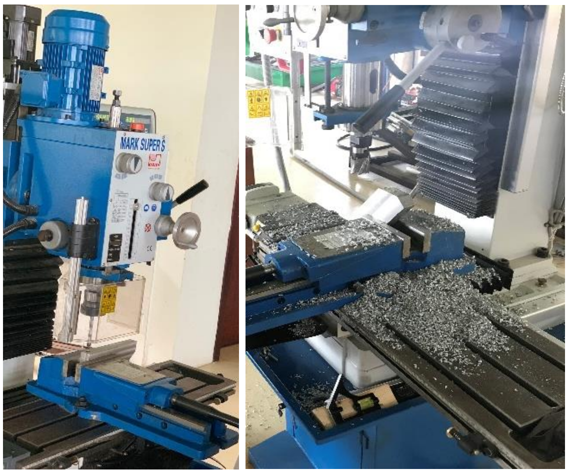

Figure 4. 6: Milling and Drilling Machine

Previously, a milling bit with a diameter of 20mm was used. However, as more experience was gained, it was decided that a milling bit with a larger surface area should be applied. Thus, the bit diameter was increased to 30mm. This increased the speed at which the fixtures were finished as a larger surface area was covered for each fixture. Moreover, with the use of the milling machine, the fixtures were cut according to the required dimension in the design drawings as seen in Appendix A. The device helped in achieving a closer tolerance for the fixtures, and a leveller was used to ensure that the fixtures being milled were always at a 0-degree angle. The finished fixture is as observed in Figure 4.7.

Figure 4. 7: Finished fixture after milling

As observed in Figure 4.7, the fixture was extremely smooth with most defects non-existent. The pattern of two different shades of colour seen on the fixture is evidence of the milling bit moving across the surface in both lateral directions (either leftwards or rightwards). The fixtures included the extension, placer, governing block and suction support.

After milling, the extension was joined to the suction support using epoxy. 'Epoxies are created by polymerizing a mixture of two starting compounds, the resin, and the hardener. When the resin is mixed with the hardener, curing is initiated. Curing is the process by which molecular chains react at chemically active sites, resulting in an exothermic reaction' [10]. The initial idea was to weld both fixtures together as that would serve as a stronger joining process. However, to weld aluminium, AC electrodes would have to be used. This type of electrodes was unavailable, and thus a welding process was not possible. The secondary idea was to attach aluminium strips to both fixtures and screw them or rivet them together. Due to the weight of the fixtures however, this method would not have been strong enough to keep the movement stable. Thus, it was finally decided that the epoxy would be used because though it was weaker than the welding process, it was able to keep the fixtures firmly bonded together.

After that, holes had to be drilled through the fixtures so that the thin and hollow aluminium rods would be able to pass through. Holes of 21mm were needed; however the drilling bit available was 22mm in diameter. Initially, the drilling machine was used to drill the holes but the stand on which it was placed was not even and the clamps used were unstable. Thus, the holes drilled were at an angle. Due to this, the milling machine was used as it could also serve as a drilling machine. With the milling machine, the clamp was more stable, and the leveller was also used to ensure that the fixture was not at an incline. Holes of 10mm diameter were also drilled at the area on the suction support where the tube would be connected to the suction cups.

4.3 Assembly of Robot Components

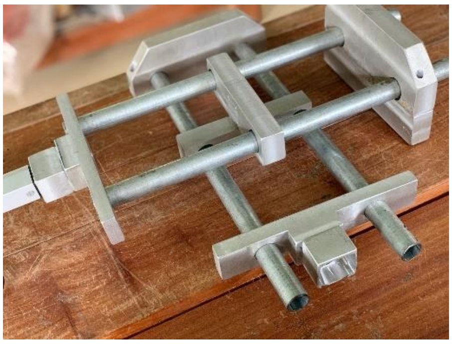

Figure 4. 8: Skeletal Frame of the Wall-C robot

After the milling and drilling process, the fixtures and hollow pipes had to be assembled. Since the welding process could not be used because of the unavailability of AC electrodes, Epoxy was used for the joining method of the components. By mixing equal amounts of the resin and hardener compounds, the parts and fixtures were firmly fixed in place in less than four (4) minutes. Figure 4.8 portrays the skeletal frame of the Wall-C robot after it had been assembled.

After that, the electrical and pneumatic components of the robot had to be assembled. Thus, fixtures that would hold the suction cup in place and allow the passage of the connecting tube from the vacuum pump had to be designed, and 3-D printed. Initially, the fixture designed had a 10.44 cm inner diameter and an 18mm outer diameter at both the top and base of the fixture. However, for the epoxy to be effective, it needs to be applied to large surface areas. Thus, the fixture was redesigned by increasing the length of the base (the target area that was attached to the suction support using epoxy). Figure 4.9 shows the 3D model of the final iteration of the fixture and the different iterations for the 3D printed accessories.

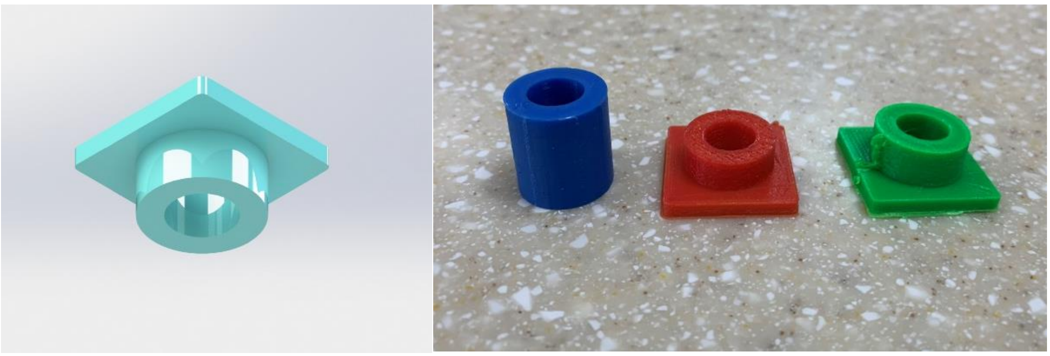

Figure 4. 9: Different iterations of the printed fixtures

After that, the fixtures were attached to each bottom hole opening on the suction supports using the resin and hardener epoxy mixture. The fixtures were attached in such a way that the hole on the fixture was placed directly over the bottom hole opening in the fixture. The suction cups were then connected through the holes and firmly attached using the epoxy mixture. The pneumatic tubes were attached through the upper hole openings on each suction support. The tubes used could handle pressures up to 10 bar, and thus they could handle the pressure that runs through them. Tee connectors served as junctions that clearly defined the path taken by each pneumatic tube. Two opposite pairs of suction cups were connected using the tubes and tee connectors to ensure that at every time four suction cups were attached to the window surface. To ensure there was no leakage in the system, epoxy was used to seal off any lining or space in any of the components that were joined together. This was to ensure that the maximum pressure was generated in the vacuum pump. Indeed, epoxy proved to be a precious tool in this project. Though four solenoid valves were used, two were attached to the skeletal frame of the robot using duct tape. The 300 mm wipers were also connected to the four legs of the robot using epoxy. The sprinkler was then attached to the governing block of the structure and the tubing which carried the cleaning solution and connected the pump to the sprinkler. The pump was then placed in the container that contained the cleaning solution. Finally, the electrical components that control the sequential movement of the actuators and the suction and release of the suction cups were connected to the Wall-C. The final assembled Wall-C robot is observed in Figure 4.10.

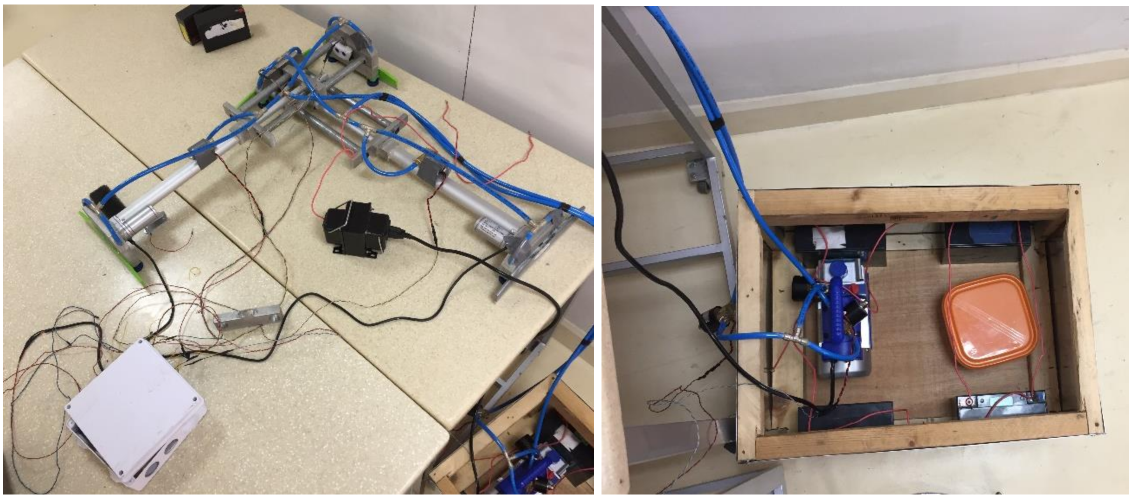

Figure 4. 10: Complete assembly of the Wall-C Window Cleaning Robot

Chapter 5: Testing and Results

The testing of the Wall-C was undertaken in two folds. An FEA (Finite Element Analysis) was performed on the 3D model of the Wall-C using SOLIDWORKS. The second test taken was the physical performance and cleaning assessment of the robot. The FEA conducted on the 3D model of the Wall-C revealed a solid frame with a safety factor of 8. The analysis further pointed to the fact that the Wall-C could sustain all forces acting on it during its natural operation.

5.1 Pressure

The focus of this paper, however, was on the physical performance and cleaning assessment of the robot. To test the stability of the robot and observe if its weight could be carried, the Wall-C was mounted on a smooth flat surface. In the analysis section, the necessary pressure required to keep the robot attached to the surface was calculated to be 17.7 kPa. The vacuum pump used could produce a maximum pressure of 150 Psi, approximately 1000 kPa.

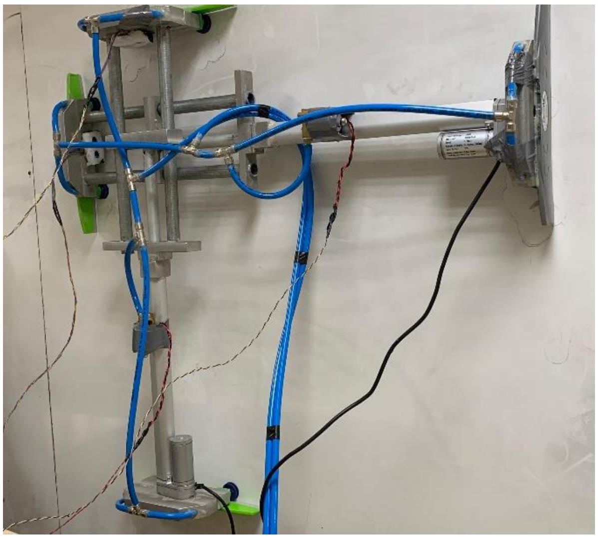

Figure 5. 1: The Wall-C scaling a plane surface

However, for complete vacuum in the suction cups to occur, the reading on the vacuum pump had to be 0. If there were no vacuum creation in the suction cups, the vacuum pump would have read 150Psi or 1000 kPa. When the Wall-C was mounted on the surface with all eight (8) suction cups experiencing the suction effect, the robot was firmly attached to the surface as observed in Figure 5.1. The pressure on the vacuum pump read 300 kPa. This meant that a pressure of approximately 700 kPa (1000 kPa – 300 kPa) was counteracting the weight of the robot and keeping it firmly attached to the target area. Alternately, when only four suction cups were triggered to experience the suction effect, the pressure on the vacuum pump read 350 kPa. Hence, a pressure of approximately 650 kPa (1000 kPa – 300 kPa) kept the Wall-C attached to the target area. The values of 700 kPa and 650 kPa far exceeded the calculated pressure required to keep the robot stuck to the surface area, 17.7 kPa. Thus, though the non-zero pressure reading on the vacuum pump meant there were tiny leakages in the robot, it was safe to conclude that the Wall-C could carry its weight.

5.2 Cleaning Assessment

The next test undertaken on the Wall-C was its movement and cleaning assessment. The cleaning of the target area relied heavily on the movement of the Wall-C and the length of the wipers because the wipers were simply connected to the legs of the robot. This simple connection meant that as the Wall-C scaled a target area, it was simultaneously cleaning that area. The movement and cleaning of the Wall-C were observed as it was mounted on the target area. It was seen that the linear X and Y movement of the Wall-C made it possible for the robot to traverse every point along the surface. However, the linear electric actuators were moving at a speed of 5.7mm/s. Moreover, the wipers used had lengths of 300 mm. Thus, the cleaning rate of the Wall-C was calculated to be:

$$Cleaning\ Rate = Length\ of\ wiper\ \times Actuator\ Speed$$

$$Cleaning\ Rate = 5.7mm/s\ \times\ 300mm$$

$$\boldsymbol{Cleaning\ Rate = 1710mm^2/s}$$

$$\boldsymbol{Cleaning\ Rate = 6.156m^2/hr}$$

Despite the simple mechanism of the Wall-C, a cleaning rate of 6.156 m^2/hr is very slow to be considered as an efficient alternative to workers who clean windows. The cleaning rate and covering percentage recorded was much lower than the Sky Cleaner 3 discussed in the literature review which had a cleaning rate and covering percentage of 125 m^2/hr and 93% respectively. This problem, however, was solely due to the kind of actuators used for the Wall-C. By replacing the electric actuators with pneumatic actuators, the speed of the cleaning robot is bound to increase substantially.

5.3 Battery Life

Bringing the Wall-C cleaning robot into context, a typical glass building in Ghana the robot is designed to work on would be the Premier Towers in the Greater Accra Region. This glass building has a total surface area of 370.5 m^2 [11]. With a cleaning rate of 6.156 m^2/hr, the robot would clean the glass surfaces of this building in 60.2 hours. This is a rather long period for a complete cleaning process and makes one consider the longevity of the batteries used in the project design.

During the testing phase of the Wall-C, it was observed that the voltage of the battery bank dropped from 11.89 to 11.36V. The drop-in voltage brought to the realization that the Wall-C's current configuration in the power supply of the system would not be enough for the Wall-C to completely clean the glass surfaces of the average building in Ghana. The analytical results are as follows:

$$Amperage = 20AH$$

$$Number\ of\ Batteries = 4$$

$$\boldsymbol{Net\ Amperage = 80AH}$$

Assuming all four pneumatic valves were active a total of 120 times for 2 seconds each time they were engaged:

$$Time\ Taken = 120 \times 2$$

$$Time\ Taken = 240s\ or\ 0.0667\ hours$$

$$Current\ per\ pneumatic\ valve = 1A$$

$$\boldsymbol{Pneumatic\ valve\ Amperage = 0.067AH}$$

For 1 hour (60 minutes), an actuator was active (either extending or retracting) for 55 minutes. Thus;

$$Current\ per\ linear\ actuator = 1A$$

$$\boldsymbol{Linear\ Actuator\ Amperage = 55AH}$$

For 1 hour, the water pump run 27 times, each time for 5 seconds:

$$Time\ Taken = 27 \times 5$$

$$Time\ Taken = 135s\ or\ 0.0375\ hours$$

$$Current\ for\ Water\ Pump = 0.3A$$

$$\boldsymbol{Water\ Pump\ Amperage = 0.01125AH}$$

Therefore:

$$Amperage\ after\ an\ hour = 80AH - 55AH - 0.067AH - 0.01125AH$$

$$\boldsymbol{Amperage\ after\ an\ hour = 24.92175AH}$$

Thus, it was evident that the Wall-C would not be able to function continuously for up to two (2) hours due to the depletion in power required to run the robot.

Chapter 6: Conclusion

Indeed, the Wall-C climbing robot could be almost revolutionary in the window cleaning sector despite the existence of similar cleaning apparatus. Its ability to scale windows alone is a step in the right direction at aiming to replace the human factor in the cleaning of glass buildings. Despite its cleaning rate of 6.156 m^2/hr, the Wall-C has the characteristic of being easily modified. Thus, its speed and cleaning rate can be increased substantially with minor changes in the design. Most commercial window cleaning devices are much smaller in size with little advancement in scaling the size to an industrial level. The Wall-C though, when compared to its closest competitor, the Sky Cleaner 3, is much lighter with a weight of approximately 15 kg and less sophisticated. Hence, scaling the size and replicating multiple products of the Wall-C would be simpler.

6.1 Limitations

It was evident that in the Wall-C project design, the aluminium fixtures were quite heavy. These fixtures coupled with the weight of the linear electric actuators contributed to the heaviness of the system and produced a high amount of stress on the suction cups. The use of Epoxy could also not be considered entirely safe. There were specific components where the epoxy mixture was not effective. Thus, these components kept falling out of place. The epoxy mixture melts at very high temperatures, and since the cleaning robot would be used mostly outdoors, this joining process would not be considered the most appropriate. Also, despite the simple movement mechanism of the electric linear actuators, they had speeds of 5.7 mm/s. Considering its stroke length of 300 mm, this was extremely slow to undertake its required tasks. Moreover, the Wall-C obtained its power source directly from the mains. Any surge in current or power outages could cause the Wall-C to fall to its destruction. This is because the response time for the grip of the suction cups to take effect is very low and any change in power levels could cause the suction cups to completely and very quickly lose the vacuum created. Finally, the cleaning system attached to the Wall-C could not be considered highly efficient. With the wipers having a length of only 300mm, large surface areas would not be cleaned.

6.2 Future Works

Due to these limitations, numerous improvements must be made to the Wall-C window cleaning robot before it can be considered for commercial and practical purposes. Due to the significant added weight of the aluminium fixtures, a better alternative would be 3-D printing the fixtures. The PLA (Polylactic Acid) plastic used to 3D print objects is not as durable as aluminium, but it is strong enough to withstand any residual stresses in the Wall-C climbing robot. In addition to its lightweight, greater accuracy could be achieved as all the dimensions obtained would be exact and replicable in multiple fixtures. Thus, machining processes such as drilling, and milling would be unnecessary.

The use of electric actuators meant the overall speed of the Wall-C robot could reach a maximum value of 5.7mm/s, a very low speed for the desired results of a cleaning robot. It would be more effective to use pneumatic actuators because they are light and much faster than electric actuators. Additionally, the linear movement of the Wall-C could not be the desired movement path for most consumers. Though the linear motion should still be considered as an option, it would be fair to incorporate a non-linear movement mechanism or system.

Moreover, to ensure that any power surges do not affect the Wall-C, it is imperative that the mains do not serve as the primary source of power for the cleaning robot. A better alternative would be a rechargeable battery powering the entire system. Another option would be to use the four (4) 12V 20AH batteries to power the Wall-C. Finally, to make the cleaning system of the Wall-C more efficient, larger wipers that cover bigger surface areas would have to be obtained, so that the target area would be thoroughly cleaned.

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Appendix A: Drawings

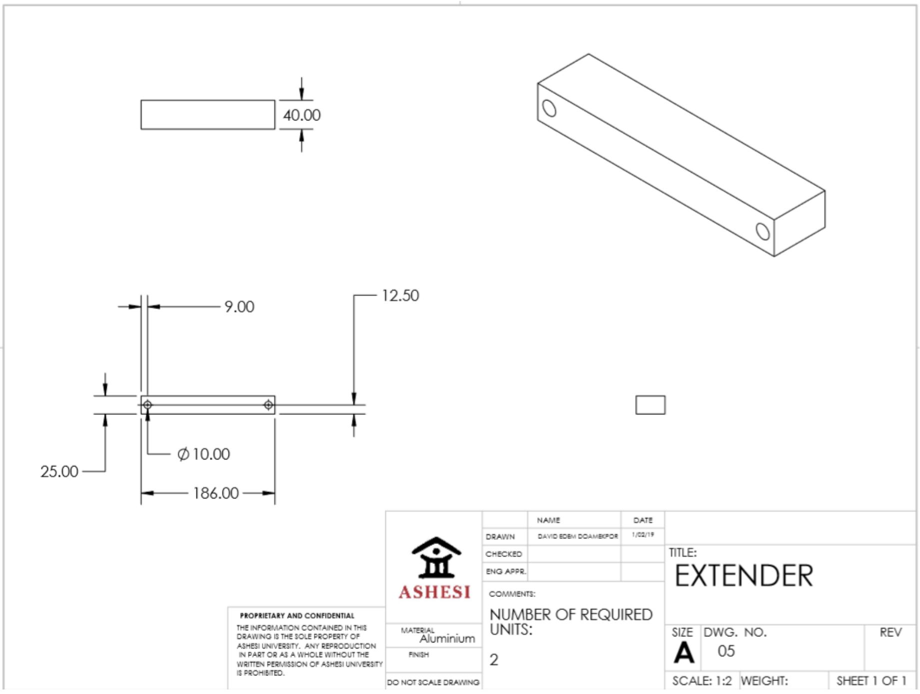

Figure A- 1: Drawing Dimensions for the Extender Fixture

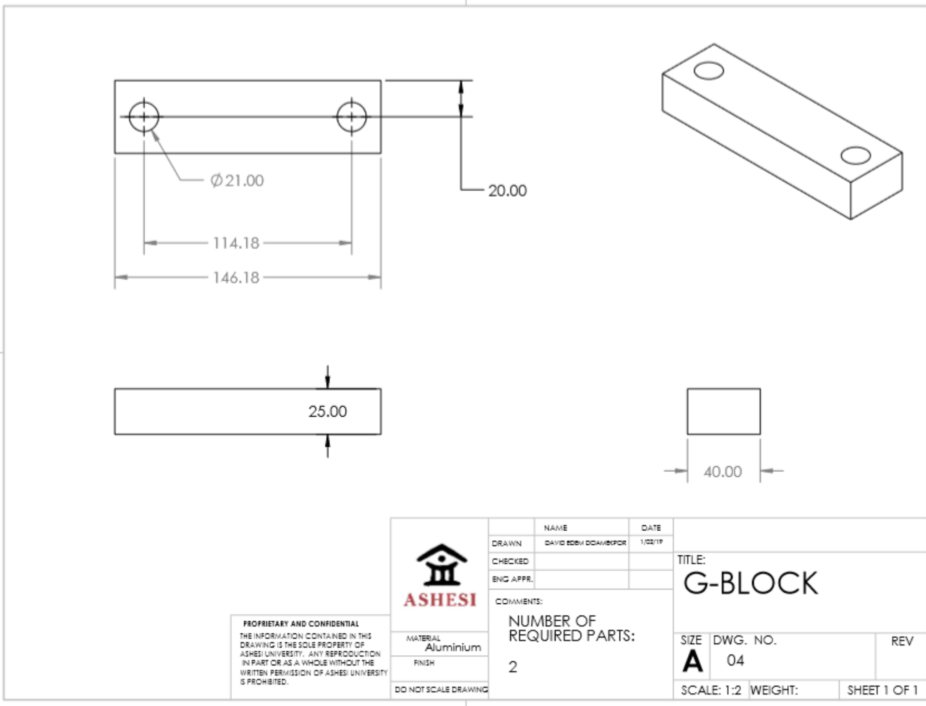

Figure A- 2: Drawing Dimensions for the Governing Block fixture

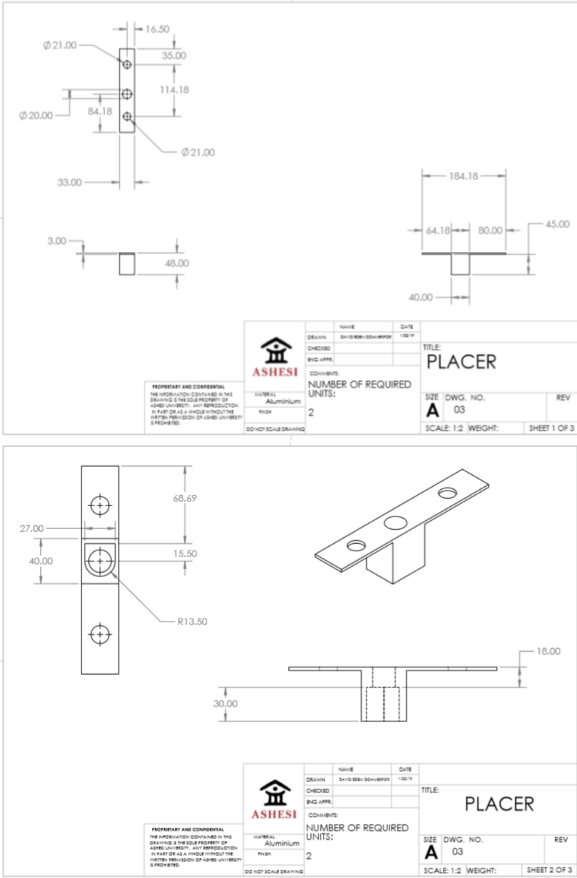

Figure A- 3: Drawing Dimensions for the Placer Fixture

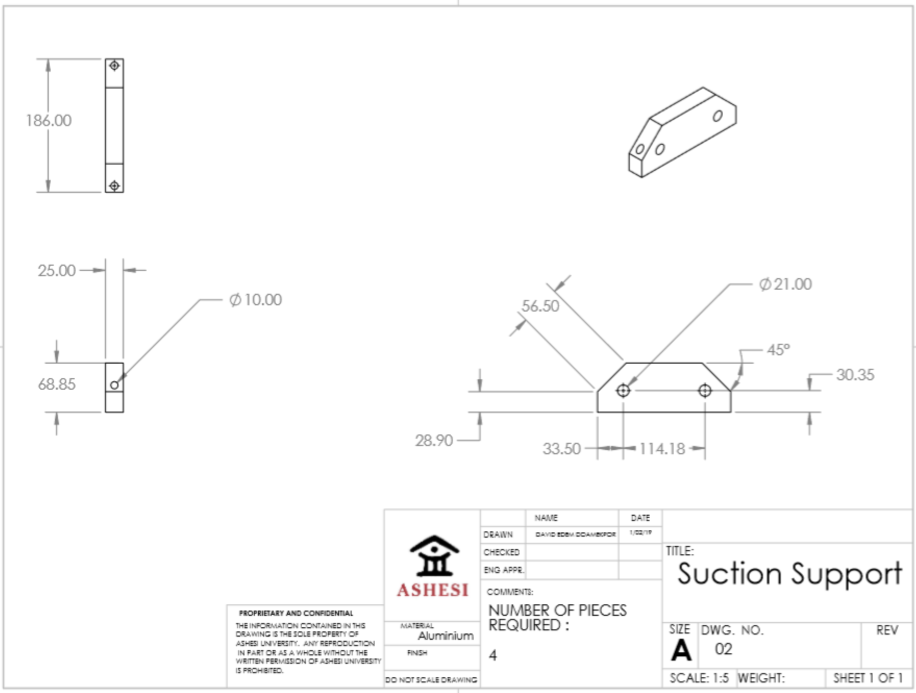

Figure A- 4: Drawing Dimensions for the Suction Support Fixture